§77. Ray-Tracing for Electron Cyclotron Waves Propagating Obliquely with Respect to Magnetic Field Lines

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A ray-tracing is a sophisticated tool, providing much insight on propagation and absorption of waves in plasmas. Its condition of validity is the following

$$|\nabla \vec{k}| << k^2$$

which states that the wavelength must not change much over a wavelength. Electron cyclotron waves in the ranges of mm-waves are sufficiently adequate for current fusion research machines. A ray-tracing code was developed for electron cyclotron heating (ECRH) in the 3-dimensional magnetic field structure of LHD [1], but in that code quasi-perpendicularly propagating waves with respect to magnetic field lines in weakly relativistic thermal plasma can only be treated.

On-axis ECRH using fundamental O-mode with 84GHz and 2nd harmonic X-mode with 168GHz from the 2O-port antenna is required for oblique injection in order to aim a electron cyclotron resonance layer at neighbor vertically elongated cross section. Because the cyclotron resonance layer doesn't across a magnetic-axis at a horizontally elongated cross section which is just positioned in front of the O-port antenna. Therefore, the existing ray-tracing code was extended so as to investigate the best condition for oblique on-axis ECRH using 2O-antenna in the LHD.

For propagation angles satisfying following condition

$$N|\cos\theta| > |1 - l\Omega/\omega|, v_t/c,$$

the relativistic down shift of the cyclotron frequency may be neglected because Doppler effect dominates. Where $N, \theta, l, \Omega, \omega, v_t$ and c mean refractive index, propagation angle with respect to magnetic field lines, harmonic number, cyclotron frequency, wave frequency, electron thermal and light velocity, respectively. We can use absorption coefficients obtained from the non-relativistic dielectric tensor for a hot Maxwellian plasma [2]. In such frame, power absorption line is decided using the conventional plasma dispersion function [3] described by

$$Z(\zeta) = i\sqrt{2}\,exp(-\zeta^2)\int_{-\infty}^{\sqrt{2}i\zeta} dt\,exp(-t^2/2)$$

which can be calculated numerically. Here, an argument ζ is defined as follows.

$$\zeta \equiv (c/v_t)(\omega - \omega_c)/(\sqrt{2}\,\omega N\cos\theta)$$

Absorption of obliquely propagating electron cyclotron waves strongly depends on its angle, plasma density, electron temperature, wave polarization and its harmonic number. Especially, it must be cared that the propagating angle dependences for the absorption of O1 and X1 modes in the finite density region satisfying a condition

$$2N(v_t/c)|\cos\theta| < (\omega_p/\omega_c)^2$$

become inverse. Much detailed descriptions are given in the reference [2].

The oblique ECRH from 2O-port antenna was tried in the magnetic configuration of R_{ax}=3.75m and B_0=1.5T although in such configuration electron cyclotron resonance exists even in the magnetic-axis of horizontally elongated cross section. The experimentally deduced heating efficiencies from the time-derivatives of plasma-stored energy when ECRH was turned off are plotted as multiple marks in Fig.1. And, color mapping of absorption ratio obtained by the new ray-tracing code is also given. Here, horizontal and vertical axes are focal potions of toroidal and height directions of the torus respectively. Tfoc = 0 and =±0.6 correspond to almost perpendicular injection to horizontally elongated cross section and obliquely injection to neighbor vertically elongated cross sections respectively.

It seems that a tendency of heating efficiency on injection angles is similar although the efficiencies deduced from the experiment is lower than expected those from the ray-tracing in whole region. One of causes would be inappropriate injection of linearly polarized waves in the experiment since in the case of oblique injection, polarization states should be elliptical to couple waves in free-space with them in plasma efficiently. This optimization will be performed in the 10th experimental campaign.

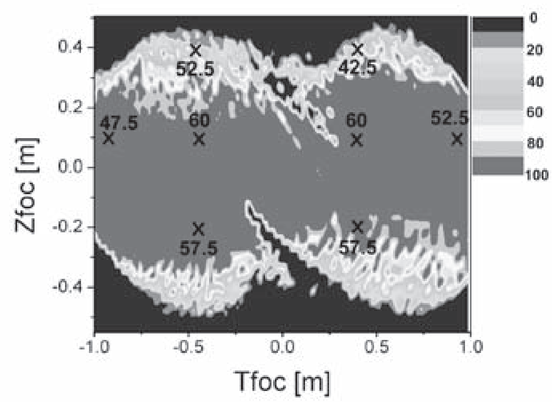

Fig.1 Comparison of absorption efficiencies between experiment and predictions from new ray-tracing code.

References
1) S. Kubo, Journal of Fus. Res. Series, Vol.5 (2002)
2) M. Bornatciti, Nuclear Fusion, Vol.23 (1983)
3) B. Fried, Academic Press, New York (1961)